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USS Virginia Ballast Tank Connector Qualification Study

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With the incorporation of impressed current cathodic protection (ICCP) into the main ballast tanks (MBT) aboard the *USS Virginia* class hulls, it was necessary to design components which would provide optimal performance and durability within the harsh environment. As part of this effort, new ballast tank anodes were selected, which consist of a platinized niobium surface extruded over a conductive copper core. This anode style is highly versatile and can be utilized in long lengths and bends to facilitate installation in the difficult tank geometry.

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USS VIRIGINIA BALLAST TANK CONNECTOR
QUALIFICATION STUDY

INTRODUCTION

With the incorporation of impressed current cathodic protection (ICCP) into the main ballast tanks (MBT) aboard the *USS Virginia* class hulls, it was necessary to design components which would provide optimal performance and durability within the harsh environment. As part of this effort, new ballast tank anodes were selected, which consist of a platinized niobium surface extruded over a conductive copper core. This anode style is highly versatile and can be utilized in long lengths and bends to facilitate installation in the difficult tank geometry.

To electrically connect the metallic anode to the ICCP electronics, a mechanical connection from the anode to a LSSHOF wire must be performed. This connection must be a low resistance path and be protected from the environment to minimize galvanic corrosion attack and possible compromise of the connection. Several connector configurations have been evaluated and two final designs by Lockheed Martin were selected for test and evaluation to meet the requirements of Electric Boat Corporation Specification No. 4155 – *NSSN Class Impressed Current Cathodic Protection System Anodes and Reference Cells.*

The Naval Research Laboratory (NRL)/ GEO-CENTERS Inc. was tasked to evaluate the prototype connectors, with the objective to determine the durability and corrosion performance of the two selected prototype anode connectors when subjected to a range of operational conditions in natural seawater. Test conditions were to simulate two significant operational states, including a worst case 10 A output scenario and a normal maximum 3 V operational output. Connectors were to be evaluated for electrical performance, degradation of the element body and for any damage or corrosion of the anode element over a six month period. This report presents the results of a six-month test and evaluation of the Lockheed Martin anode connectors and makes recommendations concerning qualification acceptance of the product for use in submarine application.

EXPERIMENTAL PROCEDURE

Eight anode connector assemblies were received from Lockheed Martin Corporation on March 29, 1999. The following two types of connector assemblies were received:

Concept C – labeled BRG-5K981014-501
Concept D – labeled BRB-5K981014-503

Concept C consisted of a solid PVC housing, as seen in Figure 1, while Concept D used a polyurethane mold at the cable connection, as shown in Figure 2. During unpacking of the connector assemblies, it was discovered that one of the Concept C assemblies was damaged in shipment. The threaded outer housing was cracked and indicated that the cap was probably over tightened during the assembly processes. Evidently a stress riser was created at a weak area of the cap, noted at the point in (Figure 3). The broken connector was returned to the manufacturer and a replacement assembly was received on May 16, 1999.

For immersion testing, the connector assemblies were placed into individual test tanks measuring 18" x 24" x 18". Each test connector was mounted horizontally in the center of the tank and supported using fiberglass structural members with attached split block PVC stand-offs, machined to the dimensions of the actual ballast tank design stand-off specifications.

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Examples of mounted connectors are shown in Figure 4 and Figure 5. The PVC stand-off was machined from PVC sheet and consisted of a split section drilled to 0.368", which was bolted together with type 304 stainless steel bolts. The 3/8" anode rod was inserted into the stand-off support and tightened firmly, suspending the connector assembly horizontally in the center of the tank. This configuration also provided a test of the stand-off material, as well as, the effect of the tight crevice area directly associated at the stand-off/anode interface. This interface was likely to be exposed to the most severe environment, because of the restrictive geometry and minimal water circulation.

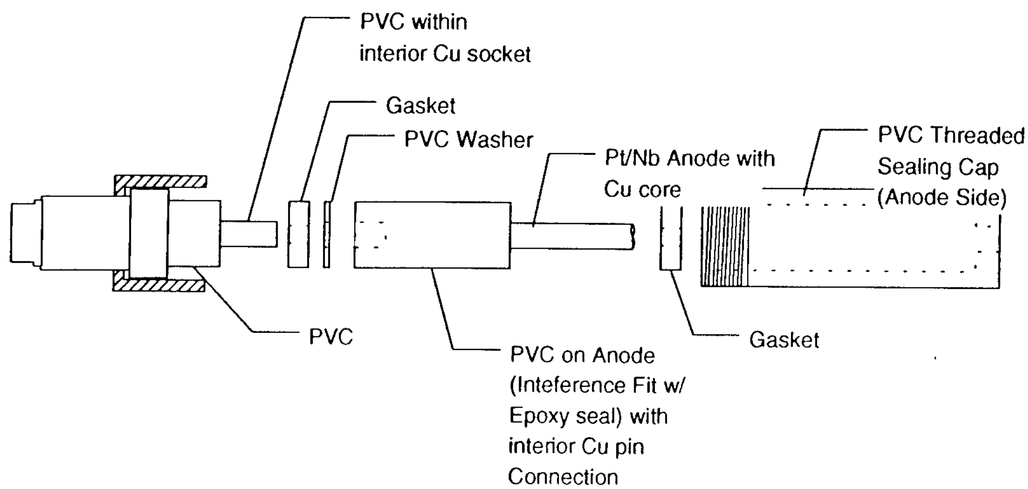

Figure 1. Schematic of MBT ICCP Anode Connector Concept C

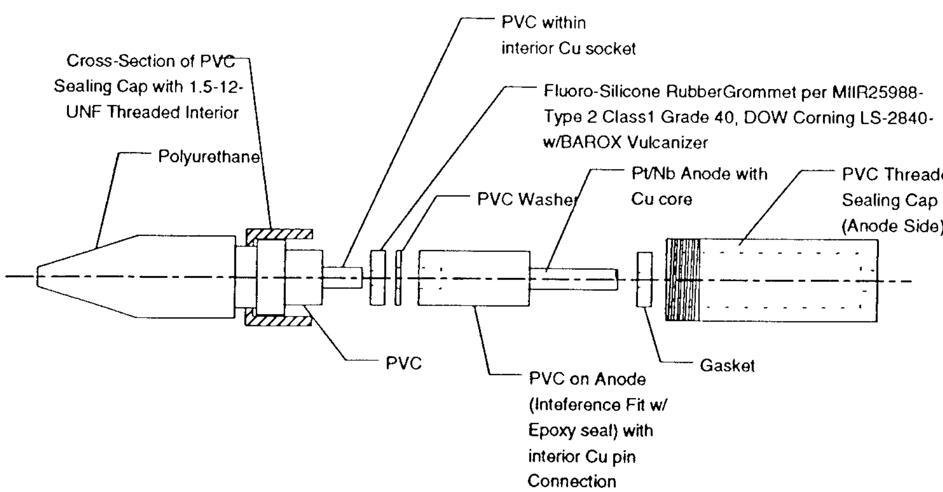

Figure 2. Schematic of MBT ICCP Anode Connector Concept D

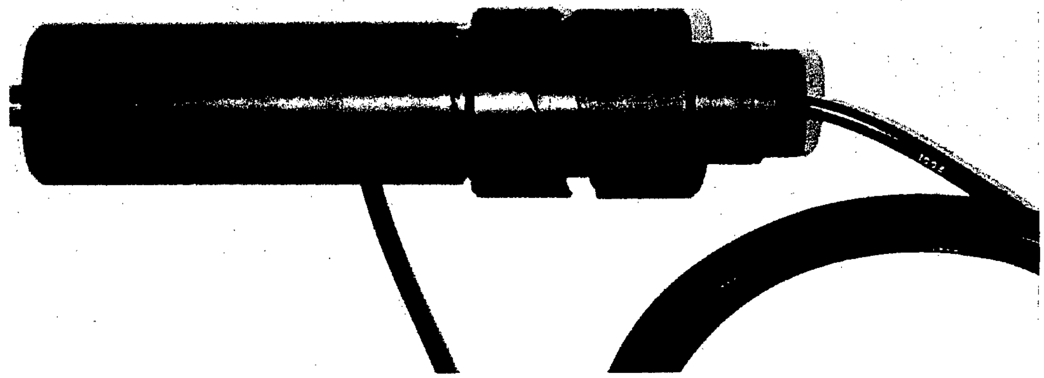

Figure 3. Photograph of Connector Failure during shipping

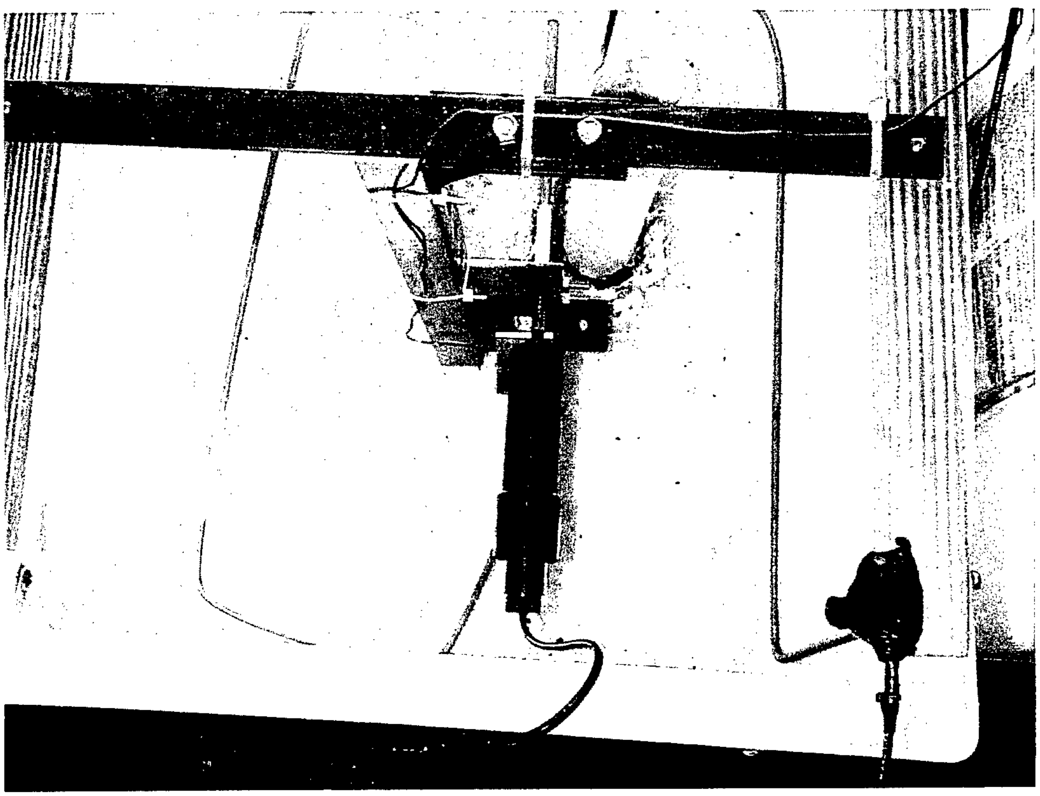

Figure 4. Photograph of Connector Concept C with entire test assembly, including reference electrode, PVC (Type 2) standoff with 304 stainless steel bolts, and Pt/Nb cathode.

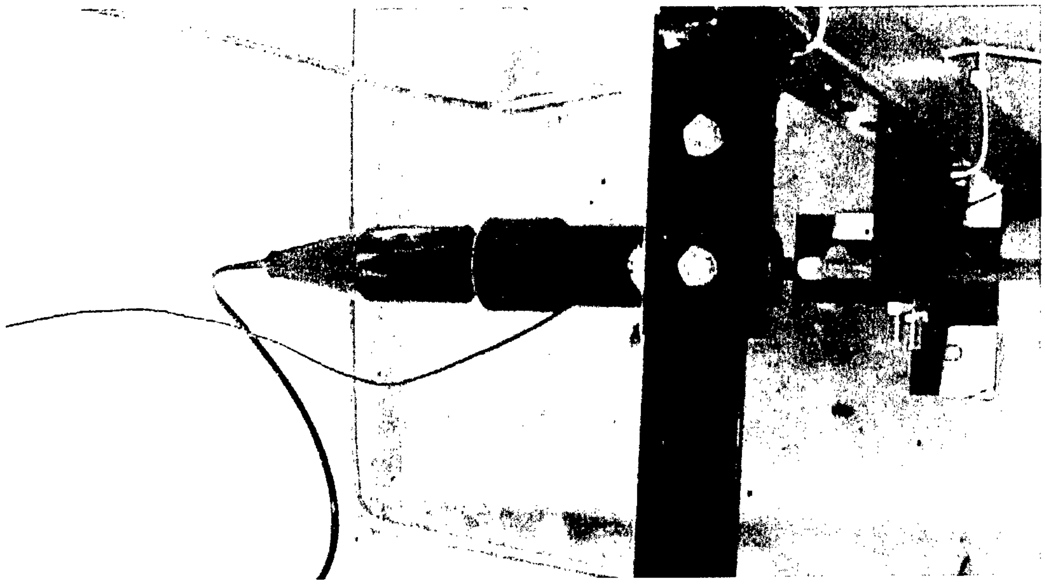

Figure 5. Photograph of Connector Concept D Test Assembly

The anode assemblies were exposed to natural seawater at the NRL Key West, FL test facility for a period of six months. Seawater physical chemistry for the period is given in Table 1. The test tanks were continually refreshed and were volumetrically exchanged a minimum of 20 times daily to maintain seawater integrity. The resultant changes in seawater chemistry produced by the enclosed operation of the anodes are given in Table 2. At these current and voltage ranges, chlorine evolution was a favored anodic reaction and contributed to determine the net effect of chlorine and high current output on the components. In operational practice, high chlorine levels would not be anticipated, but test exposure at higher concentrations was a good indication of materials durability. Other significant changes in seawater physio-chemical properties were not observed, other than the increased presence of chlorine (halogens).

Table 1. Seawater Chemistry for 4/21/99 to 10/13/99

	Temperature (º C)	Salinity	pH	Dissolved Oxygen (mg/L)	Resistivity (Ωcm)
Maximum	31.5	39%	8.2	7.0	18.9
Minimum	23.0	30%	7.8	4.8	15.6

Table 2. Test Tank Chemistry for the 3V and 10A Conditions

	Tank#	Temperature (º C)	Salinity	pH	Dissolved Oxygen (mg/L)	Resistivity (Ωcm)	Chlorinity (ppm)
Inflow	3 Volts	29.5	36%	7.96	5.94	16.5	0
Outflow	3 Volts	29.0	36%	7.75	5.21	16.5	3.3
Inflow	10 Amps	30	36%	7.85	4.57	16.2	0
Outflow	10 Amps	30	36%	8.13	5.0	16.4	>50 ppm

The anode assemblies were electrically wired to a power supply, using 10 AWG wire, to enable maximum current to be supplied by the anode to a remote cathode located within the tank. The cathode material was also a platinized-niobium wire rod and worked very effectively to facilitate the high current output required for the testing. Table 3 gives the basic connector distribution and associated test conditions. Four of the anodes (#5-8) were subjected to a "worst case" 10 A output scenario, which is the maximum output possible in the ballast tank ICCP system. While this condition is highly unlikely to occur in normal operation, successful performance under this extreme condition would cover the entire operational range and provide significant product confidence. Anodes #1-4 were subjected to the maximum optimal anode design voltage for normal operation, as determined from the physical scale modeling ICCP design effort. During the testing, the anodes were monitored for power supply driving voltage, anode potential and current output.

Table 3. Connector Type and Test Condition

Tank	Connector Type	Test Condition
1	C-501-10a	3 V DC
2	C-501-10b	3 V DC
3	D-503-10a	3 V DC
4	D-503-10b	3 V DC
5	C-501-3a	10 A
6	C-501-3b	10 A
7	D-503-3a	10 A
8	D-503-3b	10 A

RESULTS AND DISCUSSION

The average driving voltages, anode potentials and current outputs measured during the test duration are given in Table 4. Anodes #1-4 were controlled to 3V output, using a silver/silver chloride (Ag/AgCl) reference electrode, located directly below the anode surface. As a consequence, the anode current floated and changed to maintain the constant voltage. Figure 6 and Figure 7 show disassembled, 3V condition, anode connectors examined immediately after removal from test. Figure 6 shows the "Concept C" and Figure 7 shows the "Concept D" designs. Neither connector showed any sign of leakage during the test and structurally had no degradation of the PVC body, washer or anode rod. The molded polymer boots showed minor discoloration and surface texturing, but no penetration or cracking.

Anodes #5-8 were current controlled to 10 A, thus the driving voltage floated and adjusted to maintain the constant current output. Voltages as high as 11 volts were observed and were within the design parameters of the USS Virginia equipment output specification (EB #4103, Sec 3.5.3.1). Figure 8 and Figure 9 show disassembled anode connectors examined immediately after removal from test. Figure 8 shows the "Concept C" and Figure 9 shows the "Concept D" designs. Again, neither connector showed any sign of leakage during the test and structurally had no degradation of the PVC body, washer or anode rod. The molded polymer boots were not degraded over that observed in the lower voltage connectors and again had minor discoloration and surface texturing, but no significant deterioration or cracking.

Table 4. Average Driving Voltage, Anode Potential and Current Output

	Driving Voltage (V)	Anode Potential (V vs. Ag/AgCl)	Current (A)
Tank 1	6.5	3.1	5.0
Tank 2	6.5	2.9	6.0
Tank 3	6.0	2.9	4.0
Tank 4	6.0	2.9	5.0
Tank 5	10.0	5.1	10.0
Tank 6	10.0	ND	10
Tank 7	11	ND	10
Tank 8	10	4.4	10

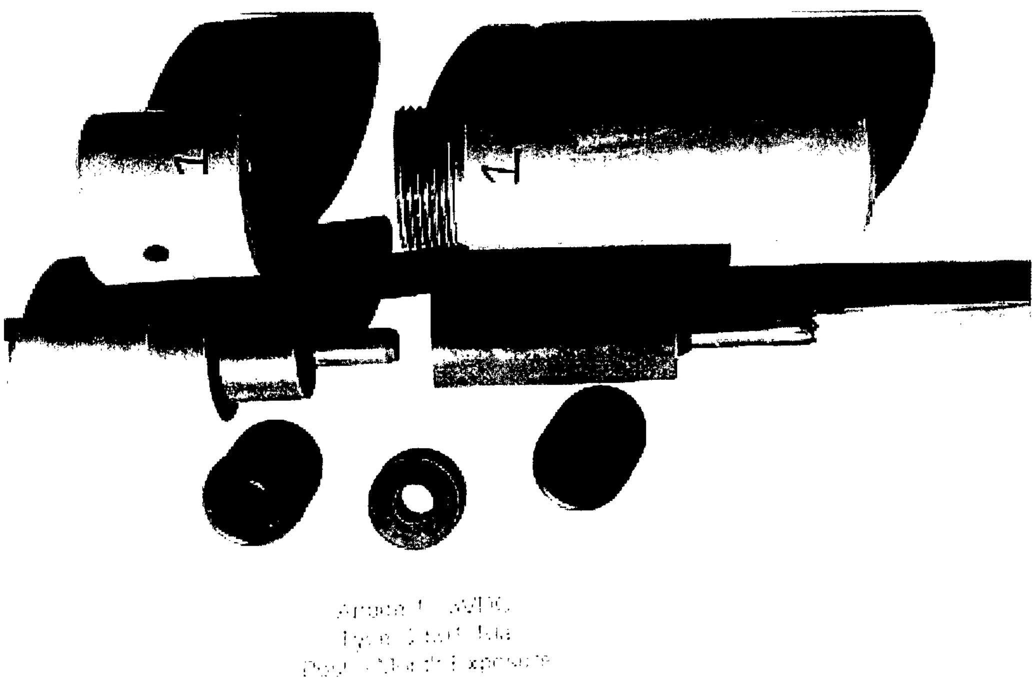

Figure 6. Post-exposure photo of Anode 1 connector assembly (Concept C), which was, tested potentiostatically at 3 VDC vs. Ag/AgCl for 6 months

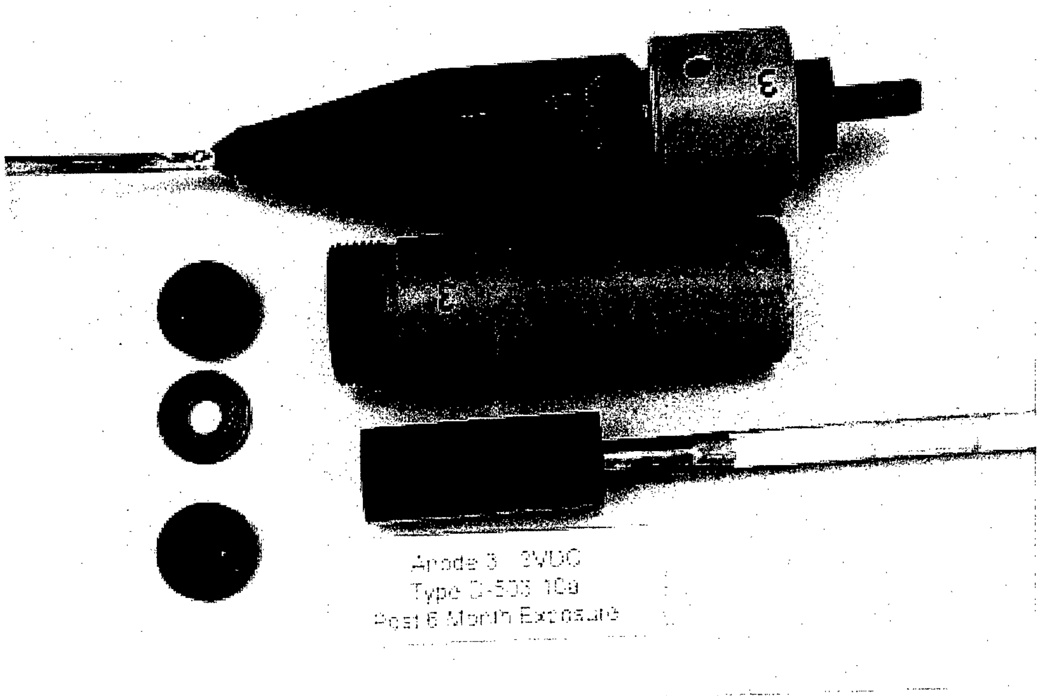

Figure 7. Post-exposure photo of Anode 3 connector assembly (Concept D), which was, tested potentiostatically at 3 VDC vs. Ag/AgCl for period of 6 months.

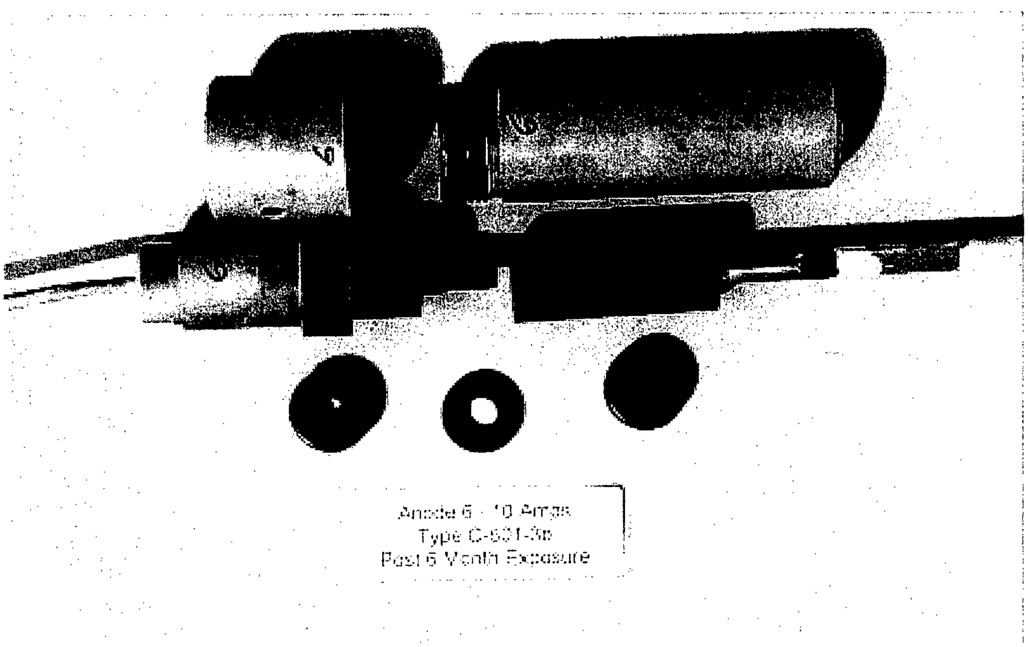

Figure 8. Post-exposure photo of Anode 6 connector (Concept C) assembly which was tested galvanostatically at 10 A for a period of 6 months.

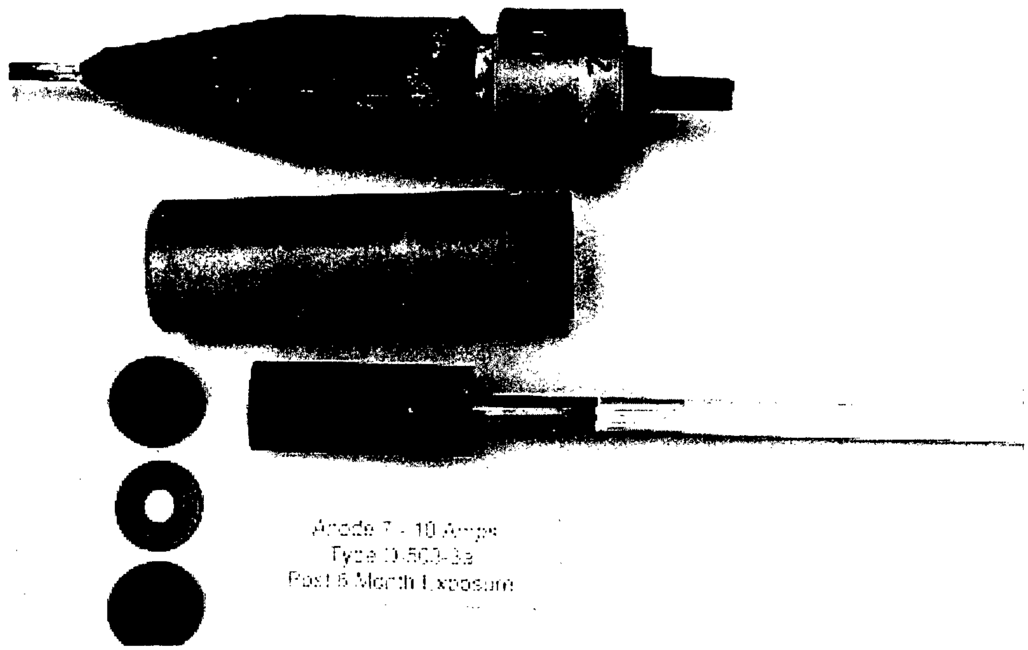

Figure 9. Post-exposure photo of Anode 7 (Concept D) connector assembly which was tested galvanostatically at 10 A for period of 6 months.

No deterioration of the Cu conductor in any of the connectors was noted, as seen on the Cu contacts, shown in Figure 10. The PVC stand-off material and 304 stainless steel bolts, shown in Figure 11, were exposed to a severe environment at the anode surface. No deterioration of the PVC was noted other than discoloration, however, the 304 stainless steel bolts were severely affected by the localized corrosion attack, possibly accelerated by the high chlorine concentration. In general, the bolts showed evidence of severe crevice attack at the most concealed surfaces and were additionally pitted at various locations. In practical application, the chlorine level would not be high, however, the environment at the anode surface could possibly generate some chlorine or create conditions favorable for crevice attack regardless of the presence of chlorine. The normal operation of the ICCP in the ballast tank has been designed to maintain voltages below the level for chlorine generation, but the possibility for crevice attack remains a corrosion issue. While not directly part of this study, use of less crevice corrosion susceptible bolts/material would be advantageous in this application.

The cable (labeled LSSHOF-03-M24643/3-01UN) used to electrically connect the anodes was found to be the material most susceptible to the presence of chlorine, as shown in Figure 12. This cable jacket showed some deterioration, but it was not significant enough to cause electrical shorting or failure. Under normal operation, the LSSHOF cable should not be abnormally affected. The molding of the electrical boot on the "Concept D" connectors, shown previously in Figure 7 and Figure 9, was the only connector feature to warrant concern. The neoprene molding, seen in Figure 13, shows a void or bubble at the cable interface. While this feature did not seem to decrease the integrity of the connector or impair the operation, improved quality control would likely eliminate this defect and any possibility for potential problems related to the stress release features of the cable boot.

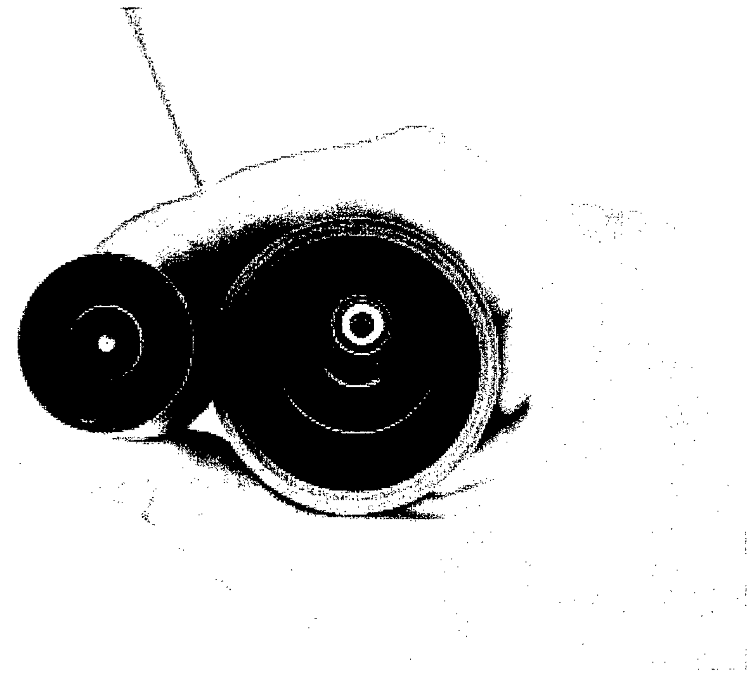

Figure 10. Photograph of interior Cu electrical connection post 6 month study.

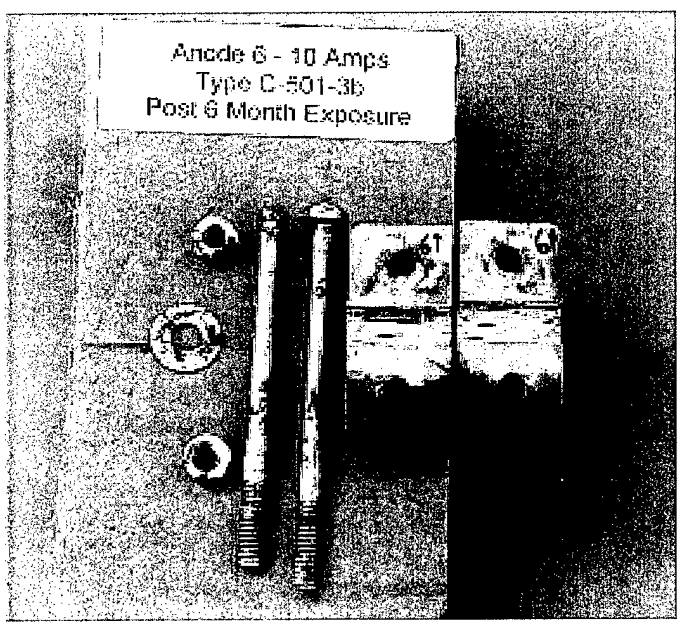

Figure 11. Photograph of damage to 304 Stainless steel fasteners and bleaching of PVC Type II anode standoff as a result of high chlorinity. Notice loss of bolt head.

Figure 12. Photograph of chlorine damage/degradation to connector cabling.

Figure 13. Photograph of poor polyethylene mold at the cable entry after immersion testing

CONCLUSIONS AND RECOMMENDATIONS

During the six month evaluation, none of the Lockheed Martin anode connectors failed as a result of exposure to seawater, under either the worst case operational condition or the maximum normal operational scenario. The anode connectors were found to be watertight during the exposure, as required, and no component was observed to have excessive degradation or problems that would preclude a failure.

The following recommendations can be made concern corrosion performance:

1. Both Lockheed Martin connector designs, concepts C and D, successfully passed the performance evaluation and both are recommended for incorporation into the Electric Boat Corp. Specification No. 4155. The "Concept C" connectors, which did not use the polymer boot, generally showed the potential for fewer problems, where chlorine might be seen.

2. Because of the mechanical failure, which occurred during shipping, it is recommended that the machine specification for the "Concept C" connector be reviewed to insure that the connector cap cannot be over-tightened and that sufficient thread length is available to insure correct tightening and sealing without stressing the PVC cap during assembly.

3. It is recommended that the molding quality assurance be carefully monitored to eliminate the presence of bubbles and voids within the stress relief boot of the "Concept D". Anode connectors should not be accepted with this type of defect.

4. The PVC mount design did not have any adverse effect on the operation or cause degradation of the anode material.

5. As no pressure cycling was performed, final connector selection would be contingent on sealing capability under operational design pressure, in conjunction with materials performance.